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DEVELOPMENT AND INVERTER TESTING OF HIGH-TEMPERATURE CESIUM-VAPOR THYRATRONS

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Prepared by
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16. Abstract

Cesium-vapor thyratrons were developed for operation at 200° C to 300° C, in a vacuum environment. The tubes were rated 15 amperes average current, 250 volts peak forward and inverse. A major effort consisted of reducing the recovery time from over 300 microseconds to less than 100 microseconds. The tubes were endurance tested over 3000 hours in an inverter circuit.

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FOREWORD

The work described herein was performed by the Tube Department of the General Flectric Company under NASA Contract NAS 3-9423 with Mr. Ernest A. Koutnik of the Space Power Systems Division, Lewis Research Center, as the NASA Project Manager.

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DEVELOPMENT AND INVERTER TESTING OF HIGH-TEMPERATURE CESIUM-VAPOR THYRATRONS

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SUMMARY

An existing cesium-vapor thyratron design was modified with the goals of reducing the recovery time from 300 to 100 microseconds and of achieving 3000 hours life. These goals were achieved by reducing the transverse dimensions of the grid aperture and by decreasing the interelectrode spacings.

Four thyratrons were constructed for endurance testing in an inverter circuit, and three of these tubes were subsequently tested to the point of failure. The design of the inverter circuit was such that the tubes could be tested at their full rating and the recovery time could be easily varied from about 30 to 600 microseconds.

INTRODUCTION

The choice of a power conditioning system for a particular space vehicle is dependent upon a number of factors, including the nature of the mission and the type of prime power source utilized.

It is envisioned that missions of two years or more in duration will become commonplace in the future and that such systems will employ a nuclear prime power source in conjunction with thermionic converters. Even if a large numer of converters are arrayed in series-parallel, the electrical output from this combination will be DC at a low impedance level. To make this power suitable for the many different loads that will exist aboard the vehicle, the DC energy must be inverted to AC energy, which can then be readily transformed to various voltage levels and transmitted to the appropriate loads. Savings in space and weight can be realized if the inverter can be located in close proximity to the power source and also be capable of operating at a frequency of several hundred hertz.

No one device currently stands out as the obvious choice to be used for switching in the inverter. Solid-state controlled rectifiers would be high in contention except for their temperature ceiling, in the vicinity of 150°C, and their susceptibility to radiation damage. The mercury ignitron has an enviable record in ground-based installations involving thousands of KVA, but the temperature ceiling for mercury is even lower, at approximately 60°C.

The thyratron with prepared (e.g. oxide coated) cathode can function with a number of different gases and vapors. With proper construction, successful operation is achieved at 700°C ambient. The life is limited, however, by constant evaporation of the active cathode material, the rate of which is a function of cathode temperature.

The cesium tube, which represents a compromise, has an intermediate temperature ceiling of 300°C, and, like the ignitron, its cathode is virtually indestructible. Additional advantages of the cesium tube, as compared to solid-state devices, are its greater ability to survive voltage and current overloads and resistance to damage in radiation environments.

A cesium thyratron design evolved during an earlier program (NAS3-6005)[1] had a recovery time in the 300 to 400 microsecond range, as compared to the desired figure of 100 microseconds sought in this program. It was decided that the most direct way to reduce recovery time to meet this objective was to reduce interelectrode spacings and grid slot size. A number of tubes were constructed following this approach until the 100 microsecond goal was achieved. Details of this design optimization effort are presented in a companion report[2] prepared under this contract. The mechanical design of the cesium vapor thyratron, the test facility, and the inverter circuit are described in the paragraphs which follow. Results of endurance testing are given, with recommended design changes based upon these results.

DEVELOPMENT GOALS

Long life, short recovery time, and the ability to operate in a vacuum environment at high temperature are the prime goals for power conditioning devices to be used in space.

Ultimate life is desirably 20,000 hours, adequate for accomplishing a two-year mission. Short recovery time is needed so that the equipment can operate at several thousand hertz in the case of rectifiers and several hundred hertz in the case of inverters. Restrictions to lower frequencies would increase the weight of the power conditioning equipment, necessitating a rêduction in pay load. The need for a high temperature capability arises because the power conditioning equipment should be capable of operating in close proximity to the nuclear power source without the need for excessive cooling equipment. This preferred location also permits short busbar runs for the low-voltage high-current DC output of the thermionic converters which convert the heat of the nuclear source to DC electrical energy.

With respect to the development program described herein, the specific goals were:

(1) to reduce the recovery time of the existing cesium vapor thyratron to 100 microseconds;

(2) to build four low-recovery-time thyratrons for the purpose of endurance testing;

(3) to log a total of 6,000 tube hours in endurance testing, using the four tubes described above.

MECHANICAL DESIGN OF THE THYRATRONS

A brief description of the cesium-vapor thyratron is presented in this section. A full account of the background leading up to the present thyratron design is given in another report[1] which covers the work of an earlier program.

The basic tube envelope of the cesium thyratron consists of four metal discs separated by three ceramic sections, Figures 1 and 2. The two bottom discs of iron are connected to the opposite ends of the spiral tungsten strip cathode, while the two top discs of copper represent the anode and grid. The copper discs efficiently conduct heat from these elements to appropriate heat sinks as required to stabilize the operating temperature. Figures 3, 4, and 5, which depict subassemblies of the final or optimized design for this development program, are indicative of the general construction of the device. In assembly, all the disc parts and ceramic sections are first stacked in the correct order, following which the weld flanges are tack-welded (to establish alignment), and then arc-welded. All welding is performed in an inert gas

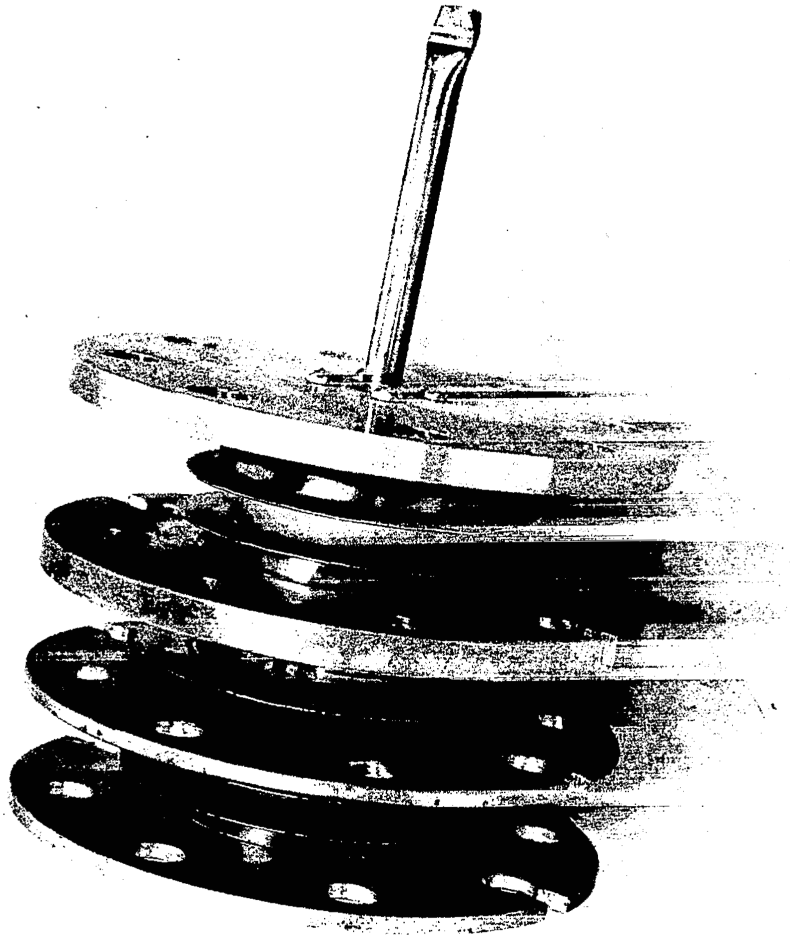


Figure 1 - Assembled Cesium Thyratron

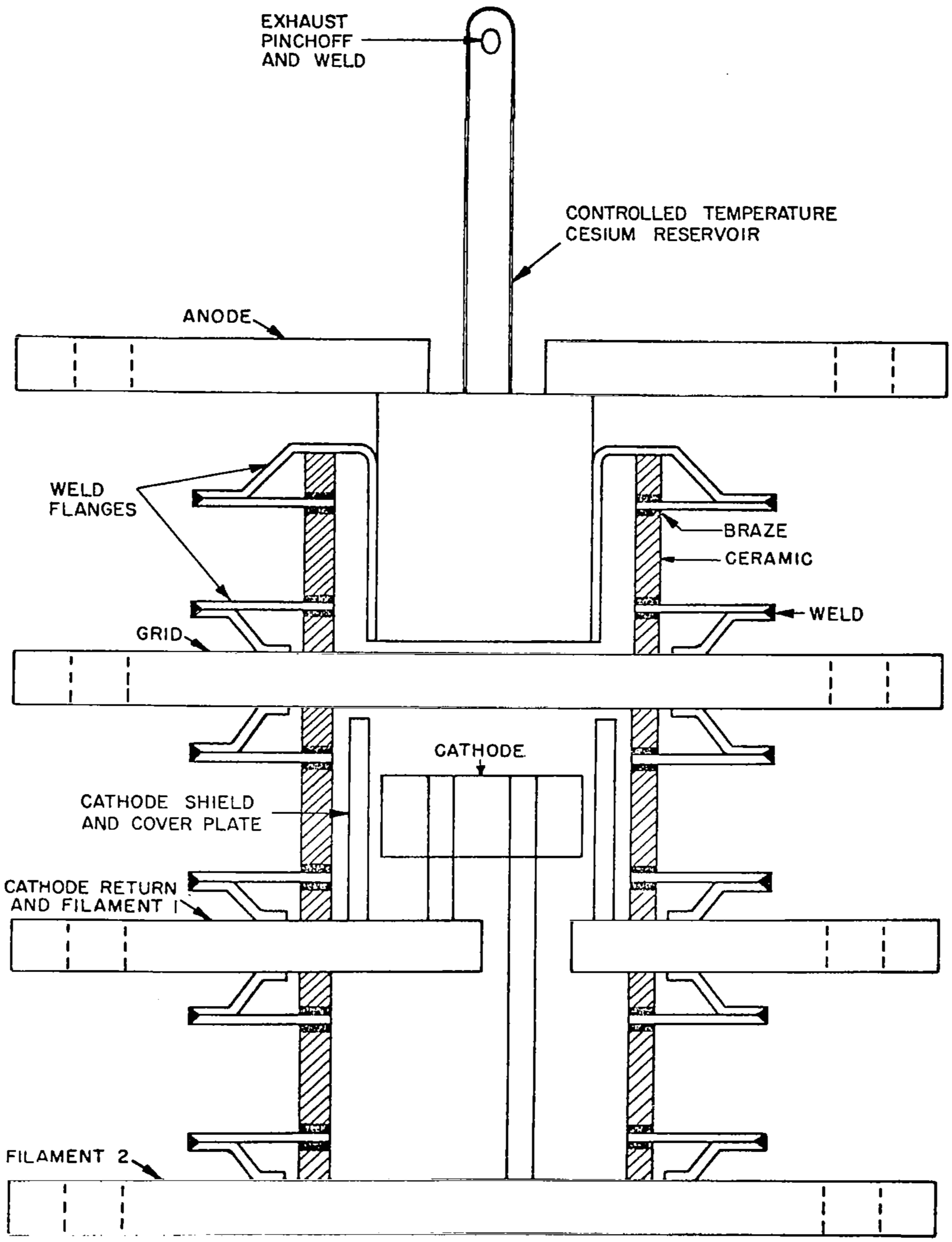


Figure 2 - Basic Structure of Cesium Thyratron

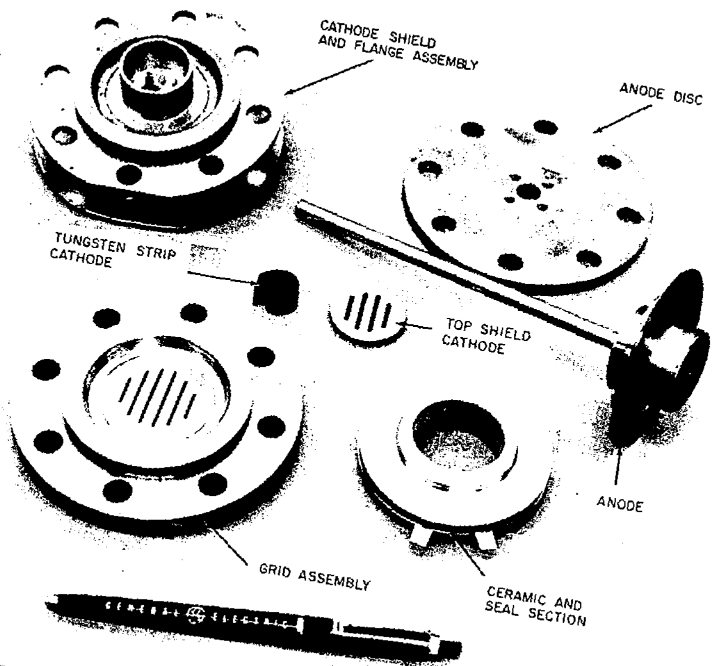


Figure 3 - Thyratron Subassemblies with Tungsten Strip Cathode Exposed

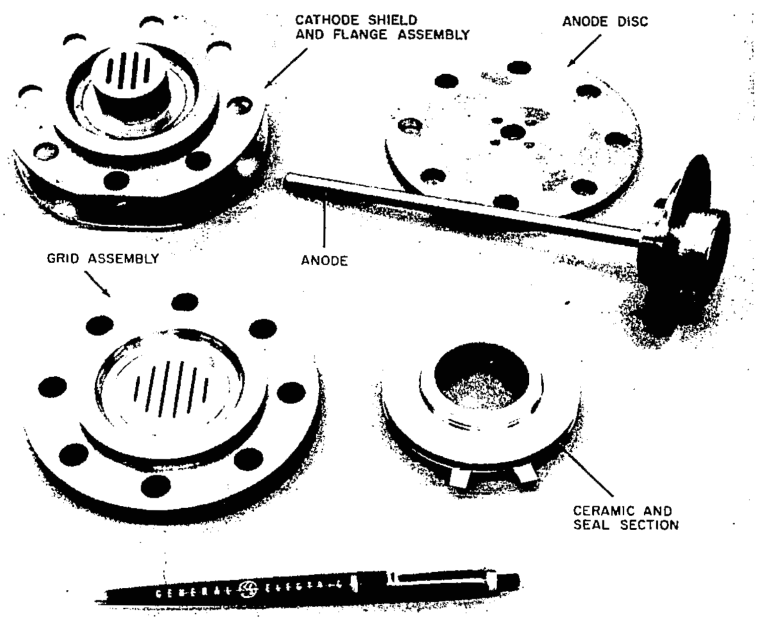


Figure 4 - Thyratron Subassemblies with Tungsten Strip Cathode and Shield in Place

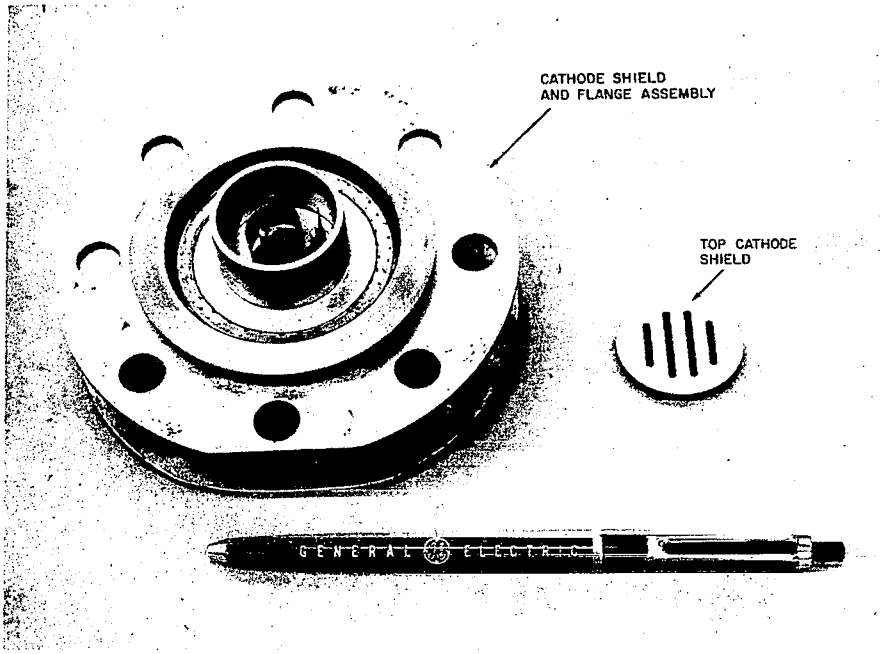


Figure 5 - Cathode Section of Cesium Thyratron

atmosphere. The weld flanges are made of tantalum, while the ceramic cylinders are made of high purity alumina. The ceramic material is brazed to both sides of the thin weld flanges by means of a palladium-copper alloy. The thick electrode discs are not sealed directly to the ceramic cylinders.

Recovery time was minimized by a systematic reduction of the distances traversed by ions in reaching a metal boundary upon which neutralization by electron acquisitions could take place.[2] Grid-to-anode spacing was reduced from 1/8 to 1/16 inch and a slotted shield was placed atop the cathode to reduce the effective spacing between the grid and cathode from about 1/4 to less than 1/8 inch. The cathode shield was 1/8-inch thick and contained 4 slots, each 1/16-inch wide, parallel, and directly below the four innermost slots of the grid. The most significant reduction of recovery time leading to the accomplishment of the recovery time goal of 100 microseconds was effected by reducing the width of the grid slots in the 1/4-inch thick grid from 3/32 to 1/16 inch, and finally to 0.037 inch, as is graphically shown in Figure 6.

ENVIRONMENTAL TEST FACILITY

Proper vacuum and temperature environments for the tubes tested in the inverter circuit were provided by two stands, each one equipped with a glass vacuum bell-jar. The pressure within the bell jars was maintained at 10^{-6} torr or less.

Figure 7 shows the layout of the 25-liter-per-second ion pump and power supplies for heating the tube under test, associated with one of the test stands.

INVERTER CIRCUIT

An inverter circuit was developed with the flexibility for conducting both the initial testing and subsequent endurance testing of the thyratrons. Recovery time could be easily varied under different conditions of applied anode voltage and current loading of the tubes. Loss of grid control or a failure to trigger properly in either tube immediately became apparent in the form of a kickout of the overload-current breaker as a result of one or both tubes carrying steady state DC.

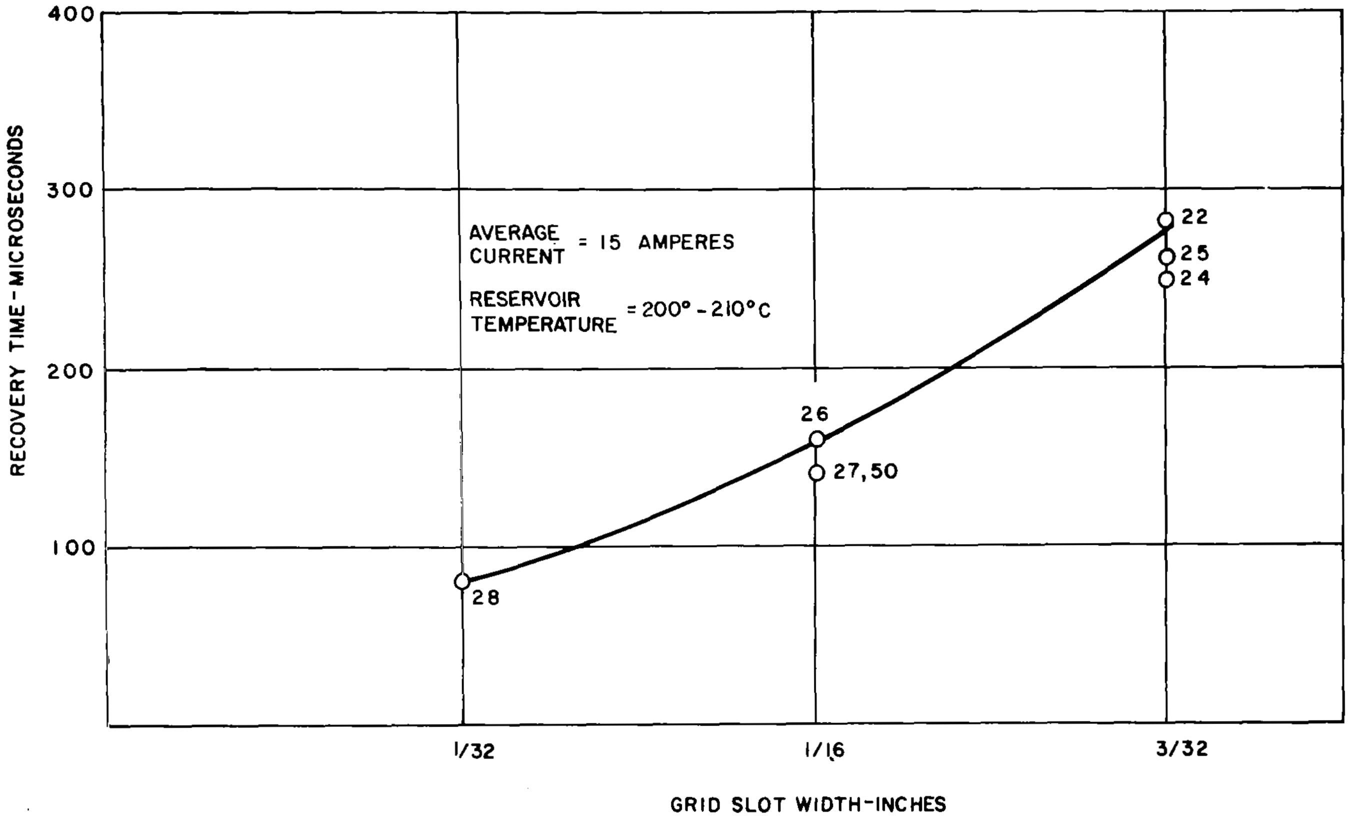


Figure 6 - Recovery Time Versus Grid Slot Width for Cesium Thyratron

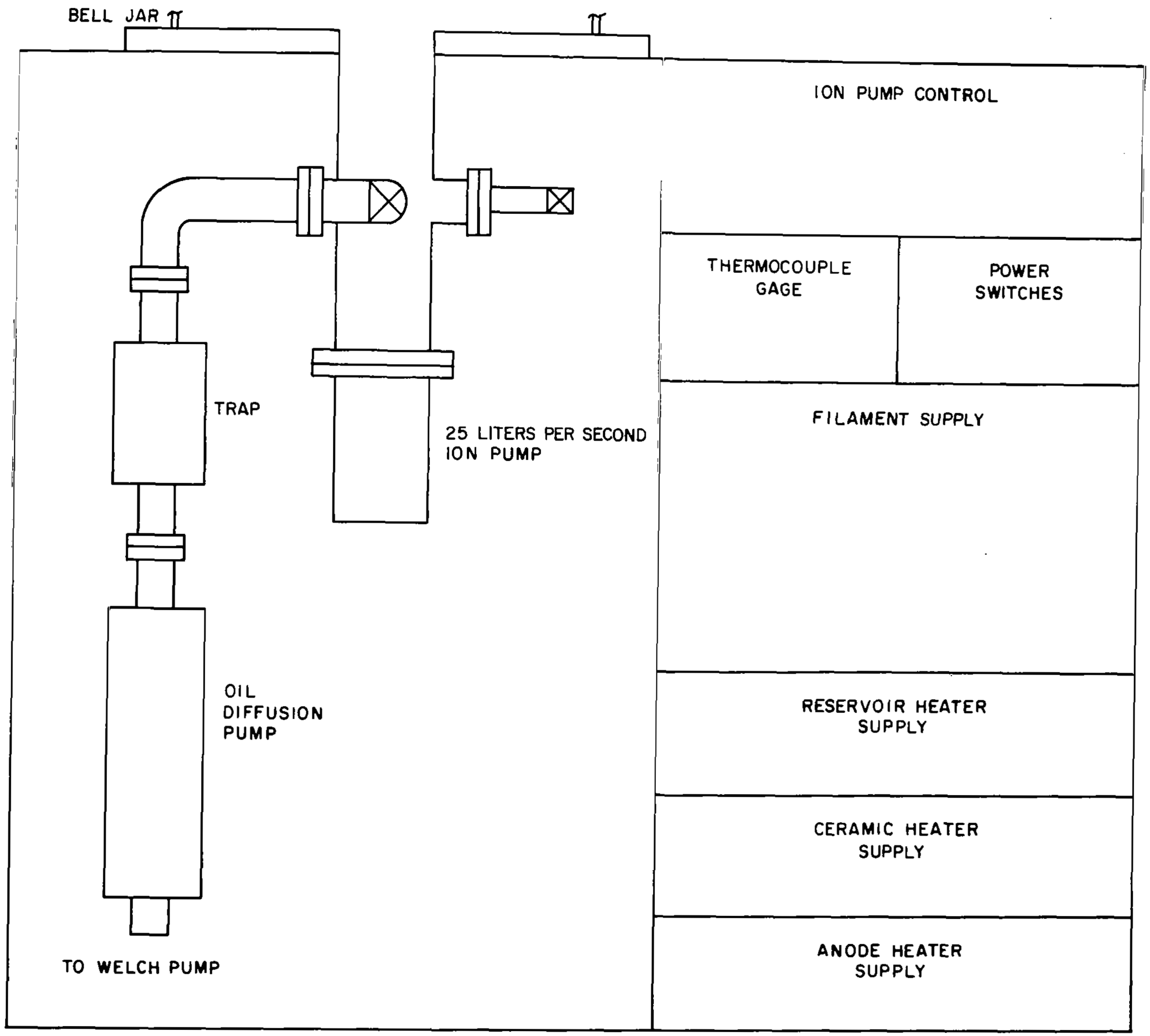


Figure 7 - Front View of Bell Jar Station

The basic circuit of the inverter is given in Figure 8. The control circuitry was integrated with the vacuum-monitoring gages in such a manner that a pressure rise in a bell jar, above a preselected value, would cause the inverter and all heater supplies for the affected tube to shut down. The trigger supply, Figure 9, was comprised of a multivibrator, cathode followers, and two out-of-phase pulse circuits using C35S silicon controlled rectifiers. The SCR output stages supplied high-current trigger pulses about 10 microseconds wide for the cesium thyratrons.

A photograph depicting various aspects of the completed inverter appears in Figure 10.

TEST RESULTS AND EVALUATION

Three cesium thyratrons were tested in the inverter, and it was confirmed that the tubes could be operated to the full 15 amperes average and at either 125 or 250 volts at the anode. The recovery times were in close agreement with the times measured outside the inverter circuit and were less than 100 microseconds.

Before a cesium thyratron can be fully loaded, various portions of it must be at certain temperatures. These are discussed in Appendix A, which delineates a procedure for starting up from room temperature.

Although all tubes could be triggered in the inverter, those utilizing constricted grid apertures for achieving the necessary 100 microseconds recovery time, such as No. 28, required more trigger energy than those of earlier design. Also, the time delay between cessation of the grid trigger pulse and the rise of anode current was increased. With a 50-ampere trigger pulse, approximately 10 microseconds wide, the anode current of No. 28 did not start until approximately 10 microseconds after the grid pulse had terminated. This indicates that ions produced in the grid-cathode region by the trigger pulse must drift through the grid slots until influenced by the anode field. In cases where anode conduction is initiated after the grid pulse has terminated, there is a chance of intermittent conduction. This is because the drifting ions are always subject to deionization at a time when there is no new ion generation taking place. It was found that if anode delay time (the time between application of grid pulse and the initiation of anode current) exceeded 25 to 30 microseconds, the tube would fail to "pick up". The anode times were measured by displaying the trigger pulse and the anode voltage

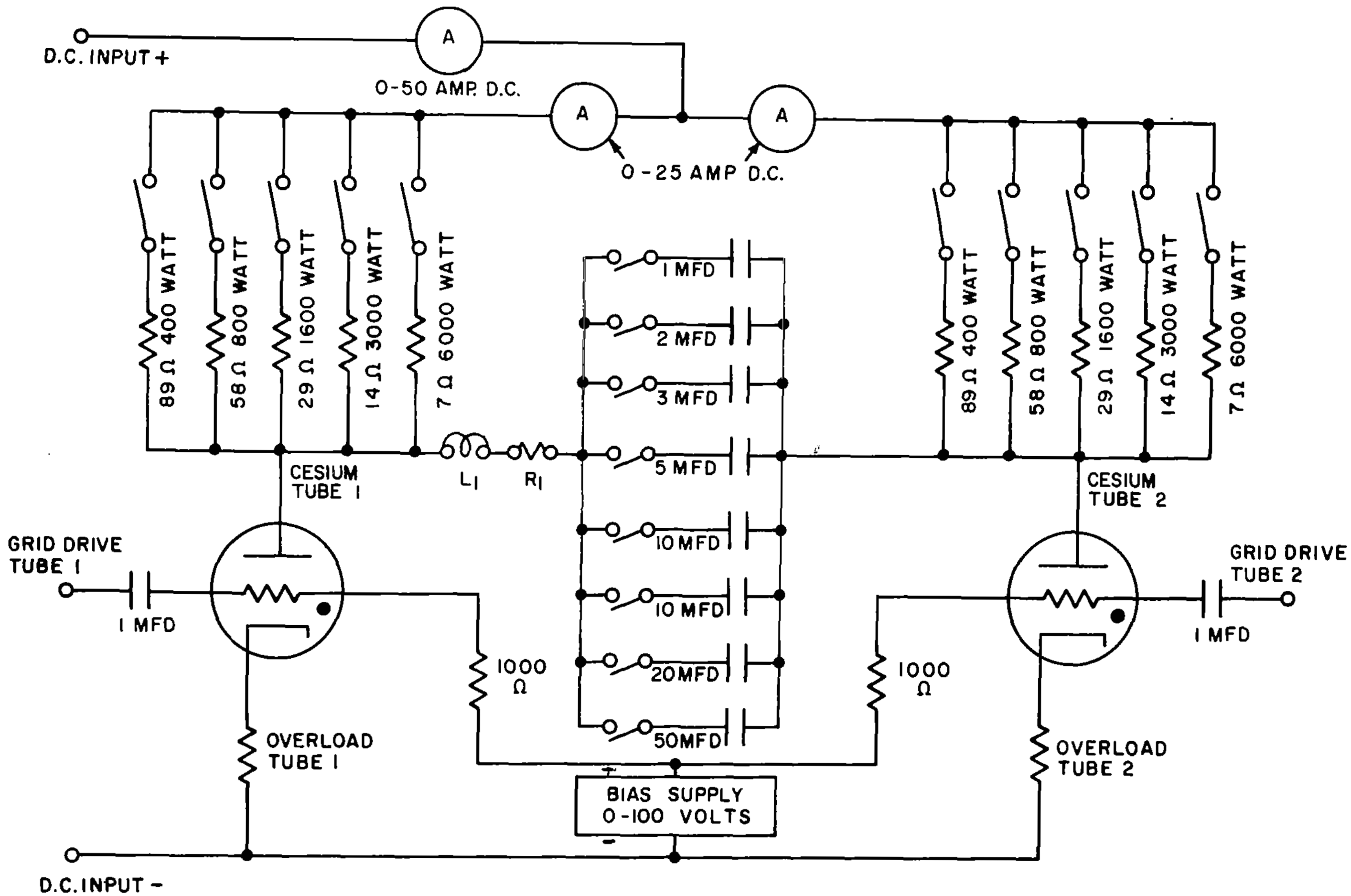
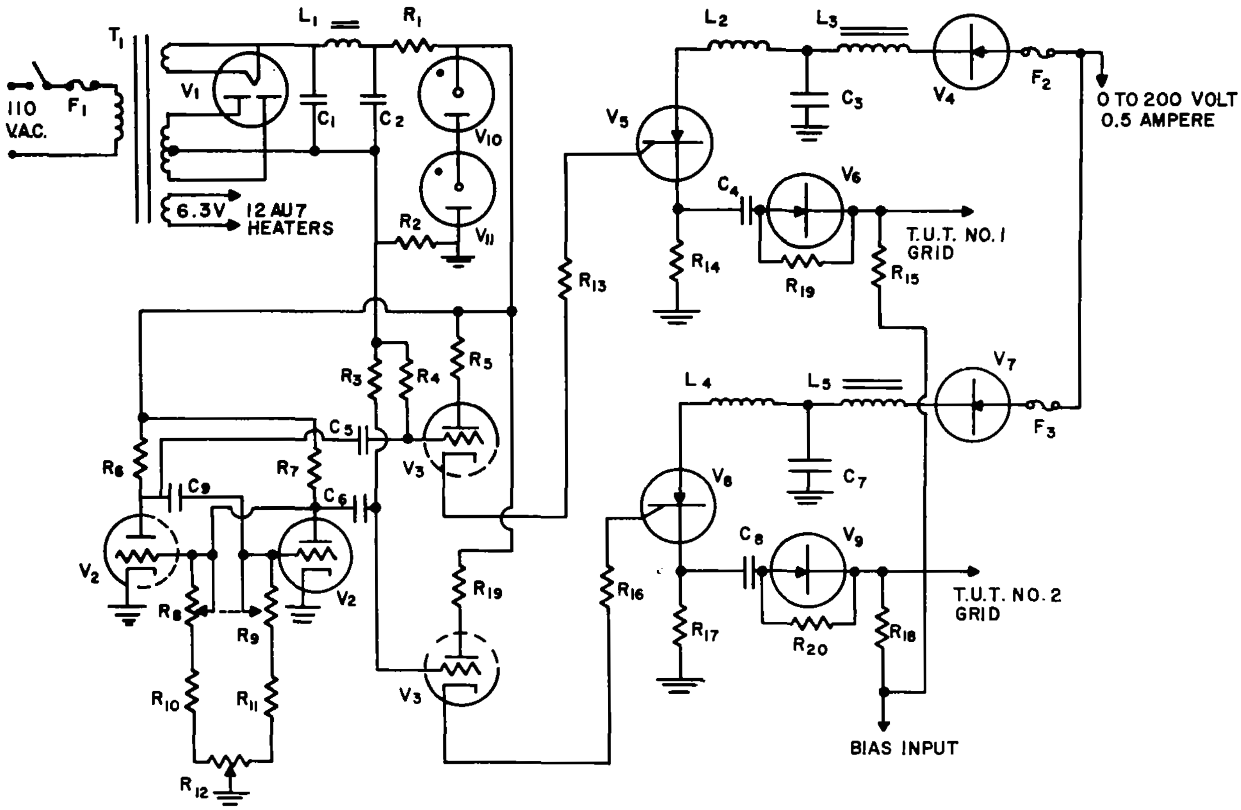


Figure 8 - Inverter Load and Commutating Circuitry



Symbol	Description	Symbol	Description
T_1	360 - 0 - 360V at 80 ma DC	R_{15}, R_{18}	100 ohm, 25 watt Resistor
	5V at 2A, 6.3V at 2.5A Transformer	R_{19}, R_{20}	1000 ohm, 10 watt Resistor
L_1	8 henry 150 ma DC Inductance	C_1, C_2	20 mfd 450 volt Capacitor
L_2, L_4	20 microhenry Inductance	C_3, C_7	1 mfd 600 volt Capacitor
L_3, L_5	4.5 henry 200 ma DC Inductance	C_4, C_8	2 mfd 600 volt Capacitor
R_1	2000 ohm, 10 watt Resistor	C_5, C_6	0.0015 mfd Capacitor
R_2	500 ohm, 2 watt Resistor	C_9, C_{10}	0.002 mfd Capacitor
R_3, R_4	22,000 ohm, .5 watt Resistor	F_1	2 ampere fuse
R_5, R_{19}	4700 ohm, 2 watt Resistor	F_2, F_3	.25 ampere fuse
R_6, R_7	10,000 watt, 2 watt Resistor	V_1	5Y3 rectifier
R_8, R_9	1 megohm potentiometer	V_2, V_3	12AU7 double triode
R_{10}, R_{11}	75,000 ohm, .5 watt Resistor	V_4, V_7	4JA27P silicon rectifier
R_{12}	100,000 ohm potentiometer	V_5, V_8	C355 silicon controlled rectifier
R_{13}, R_{16}	1200 ohm, 1/2 watt Resistor	V_6, V_9	IN2484 diode
R_{14}, R_{17}	5 ohm, 25 watt Resistor	V_{10}, V_{11}	OA2 voltage regulator

Figure 9 - Inverter Trigger Supply

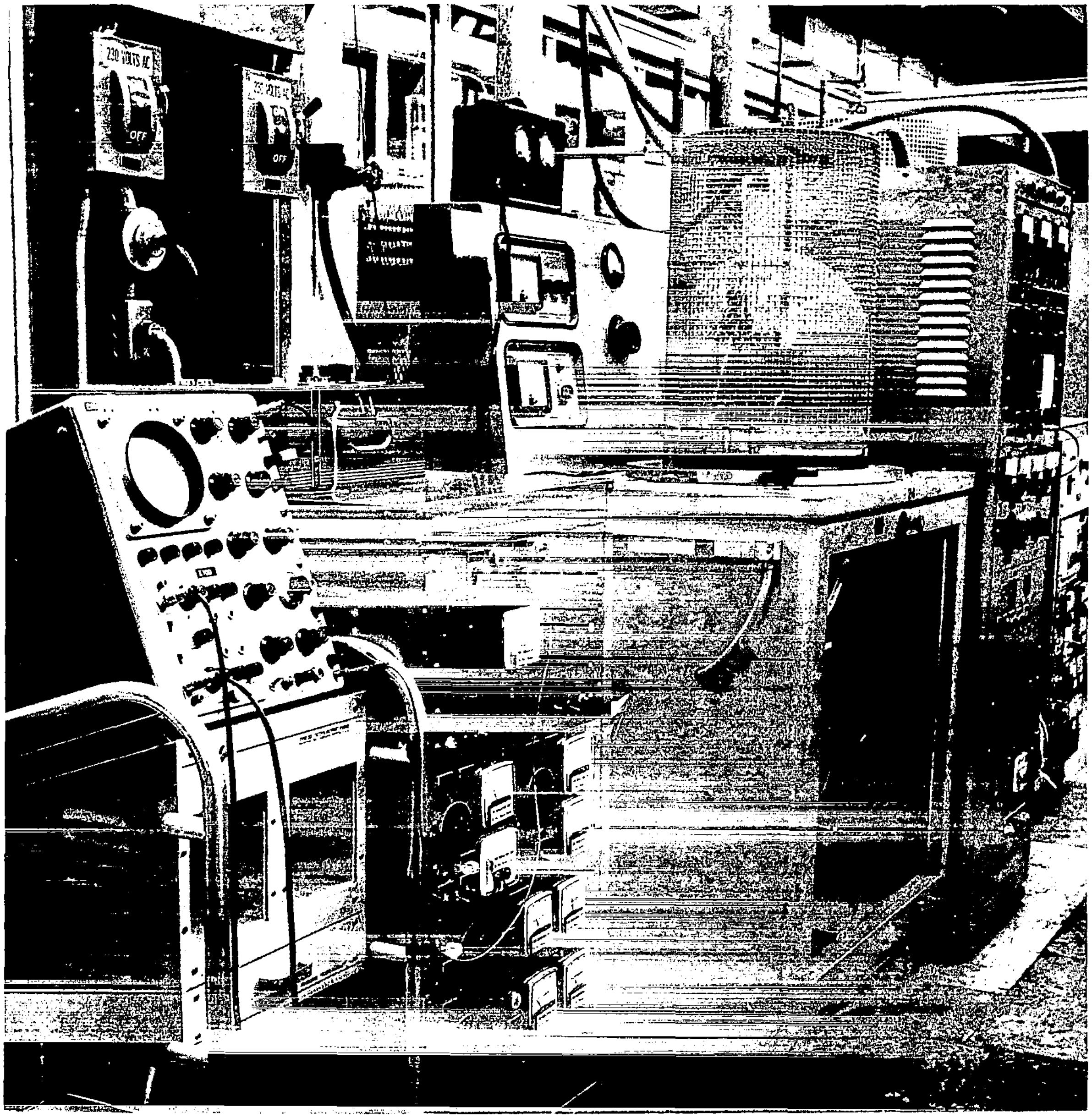


Figure 10 - Bell-Jar Station With Power Supplies

pulse for one tube on a dual-channel oscilloscope. The anode delay could be varied by varying the amplitude of the trigger pulse. Anode delay times also tended to increase as anode current increased. This is illustrated in Figures 11 through 14, a series of photographs of superimposed grid pulses and anode breakdown traces for average currents from 10 to 15 amperes. At 10 amperes average, anode breakdown is well ahead of the end of the trigger pulse, while at 15 amperes, anode breakdown is long after the end of the grid pulse. The 14-ampere case is an interesting transition case in which some of the breakdowns occur at the end of the grid pulse while the rest occur about seven microseconds later. The anode delay time variation versus average current which was observed during steady-state operation could be ascribed to the extra heating within the tube at the higher currents. Such heating tends to reduce the vapor density, and the process, if carried far enough, produces a condition in which the probability of ionization is reduced -- hence, the longer delay times.

Since the inverter circuit was an RC type circuit, the wave shape of the anode voltage during the recovery time period of the tube was identical to that experienced when tested outside the inverter. This is confirmed by the oscillogram of anode voltage shown in Figure 15. The trace at the centerline of the scope depicts the tube drop during conduction, while the top of the square wave is the supply voltage during the non-conducting period. Note that the commutating capacitance causes the voltage to swing more than 250 volts negative after conduction. The circuit then rapidly charges back to the forward supply voltage. In this illustration, the repetition rate is about 250 pulses per second, and the recovery time is about 100 microseconds.

The rate of fall of anode voltage immediately after cessation of current conduction determines the magnitude of inverse voltage that is applied during deionization of the tubes. If the rate of fall of voltage is too fast, the tube is likely to arc back.

Figure 16 portrays an expanded sweep picture of the rate of fall of inverse voltage immediately after conduction. The 600 volts per microsecond rate of fall is the maximum obtainable in the inverter circuit, but this figure can be reduced considerably by connecting a capacitance between the anode and cathode of the tube being studied. In a later section, it will be noted that the performance of tube No. 31 was improved by the connection of a 1-mfd capacitor from anode to cathode. This reduced the anode voltage rate of change to 20 volts per microsecond as shown in Figure 17.

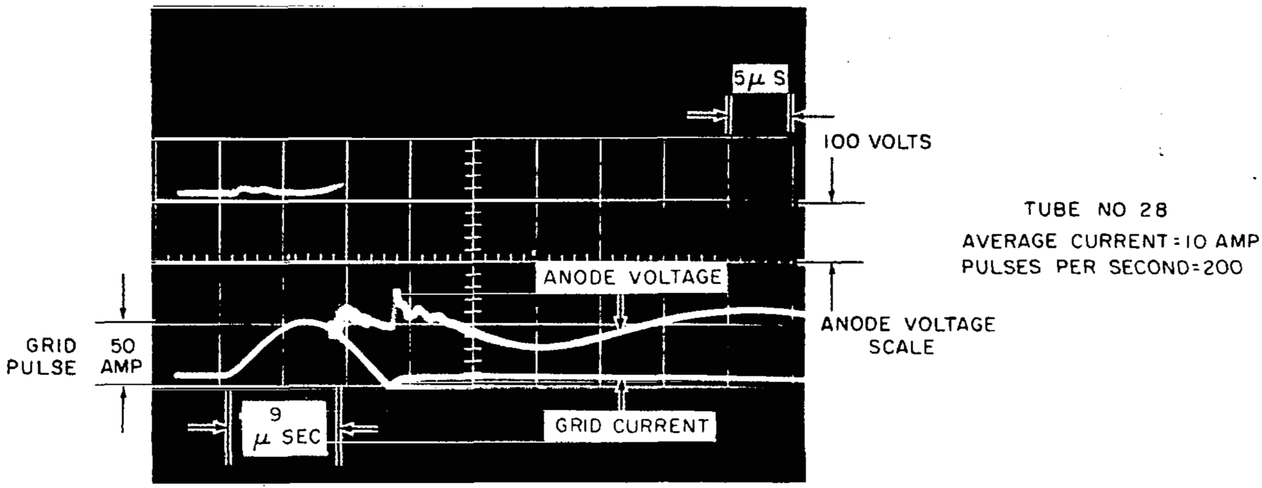


Figure 11 - Anode Delay Time for Average Current of 10 Amperes

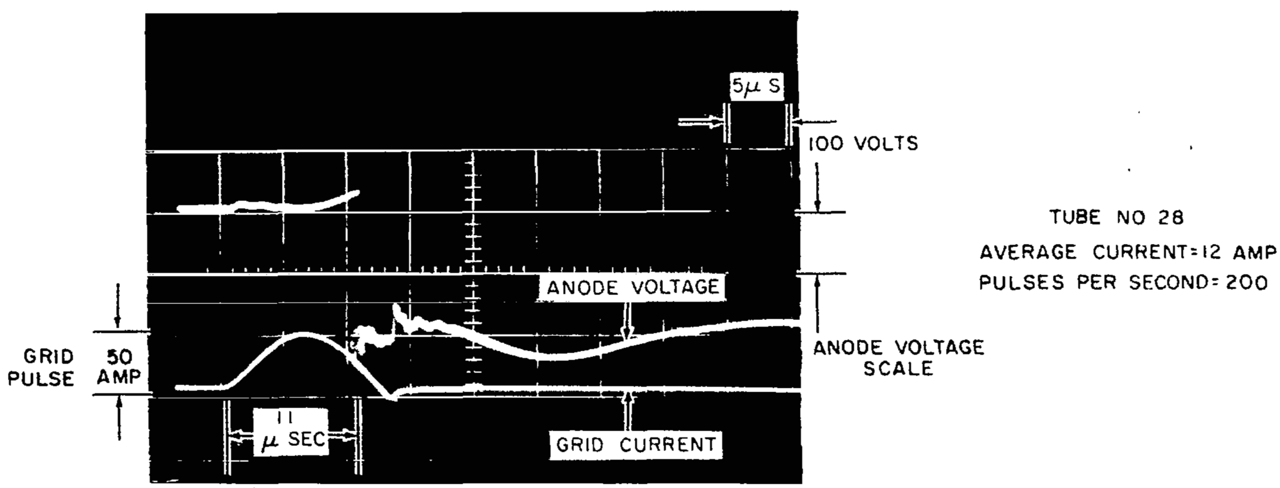


Figure 12 - Anode Delay Time for Average Current of 12 Amperes

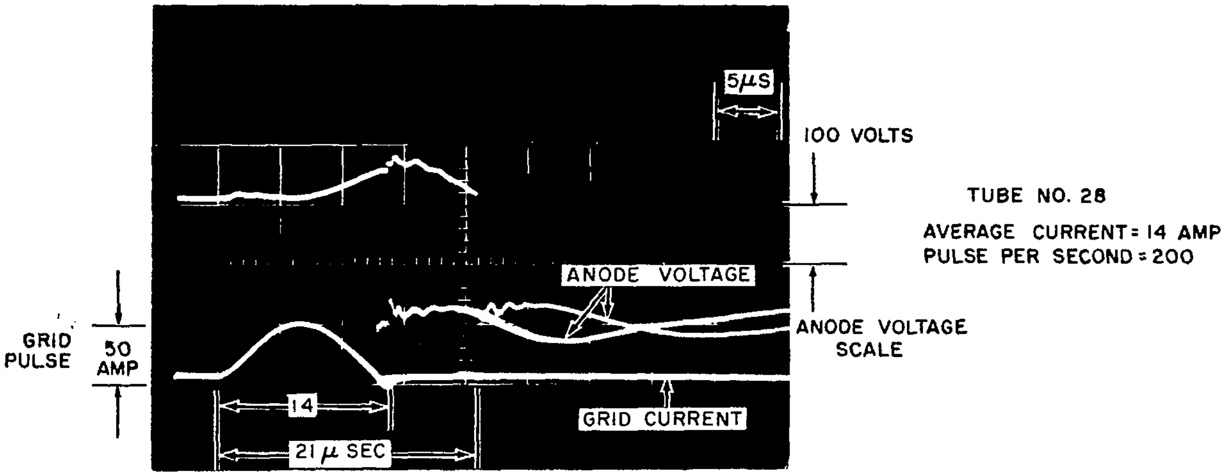


Figure 13 - Anode Delay Time for Average Current of 14 Amperes

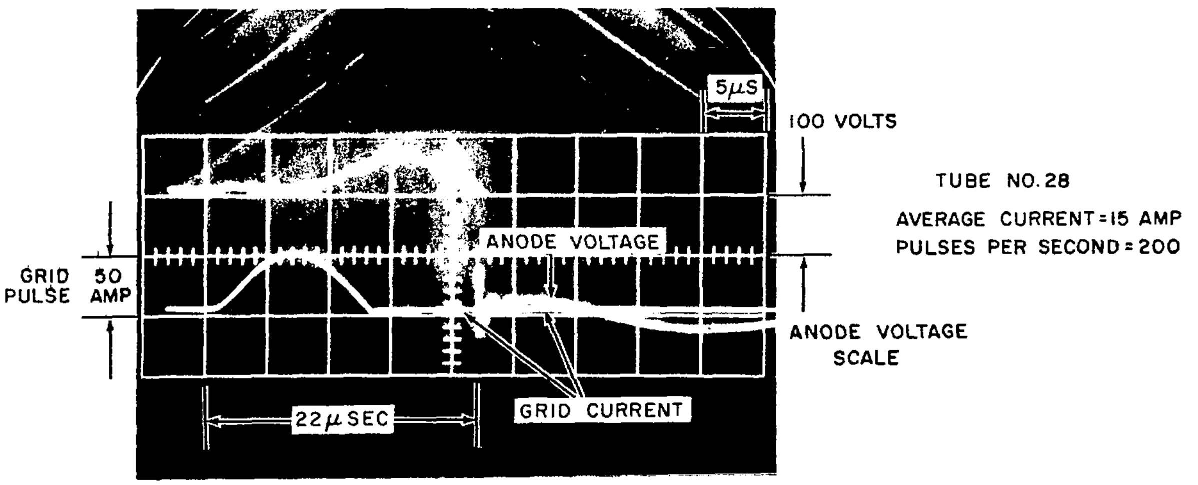


Figure 14 - Anode Delay Time for Average Current of 15 Amperes

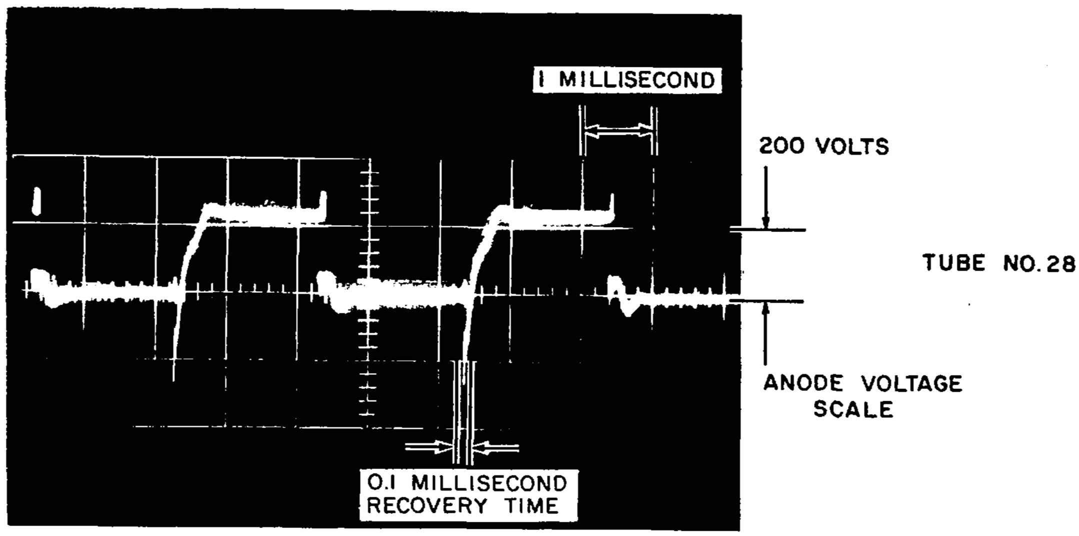


Figure 15 - Anode Voltage Wave Shape for Inverter Operation

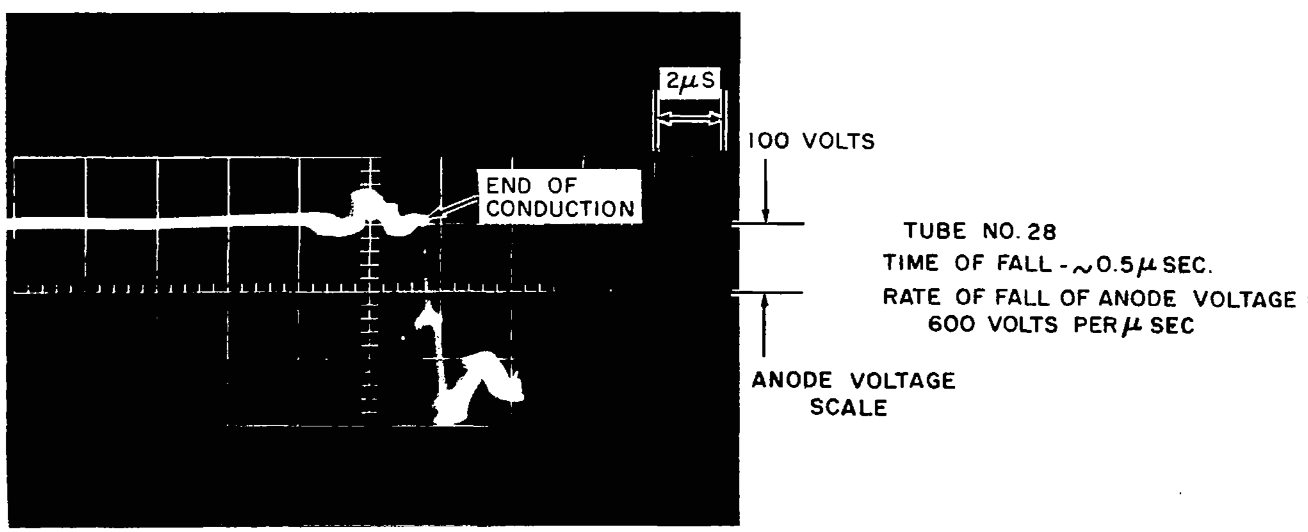


Figure 16 - Rate of Fall of Inverse Voltage for Inverter Circuit

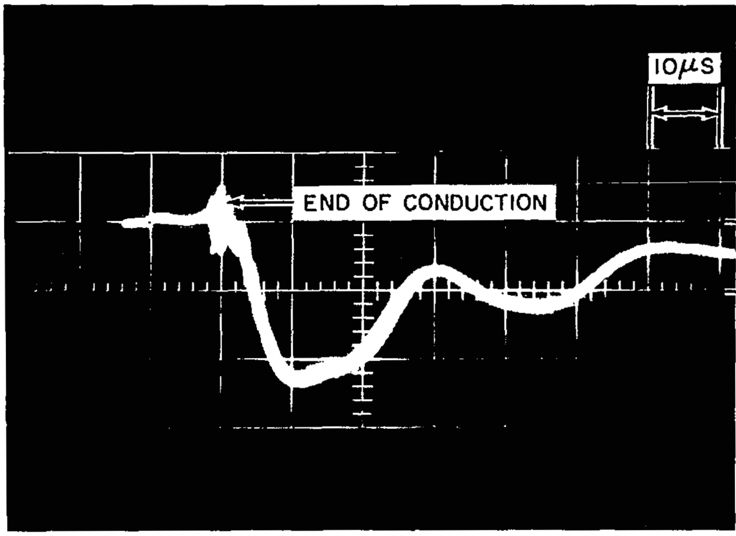


Figure 17 - Rate of Fall of Inverse Voltage with Capacitor Connected

The shortest recovery times measured during this program are shown in Figures 18 and 19 for tube No. 28*, with the circuit set (by means of selecting particular values of commutating capacitance) to produce recovery times of 80 and 55 microseconds respectively.

Four thyratrons -- Nos. 28, 30, 31 and 32 -- were constructed for the purpose of achieving 3000 hours of endurance testing in the inverter. All tubes had nominal interelectrode spacings of 1/16 inch and grid slots of 0.037 inch in width. Tube No. 31 differed from the other three tubes in two respects, both of which were intended to facilitate tube assembly:

(1) Welding flanges were of Ceramvar**, a nickel iron alloy, instead of tantalum.

(2) Anode was of copper instead of tantalum.

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*The serial numbers of the tubes given throughout this report bear no relationship to the quantity of tubes made for this investigation.

**Wilbur B. Driver Company, 1875 McCarter Highway, Newark, New Jersey

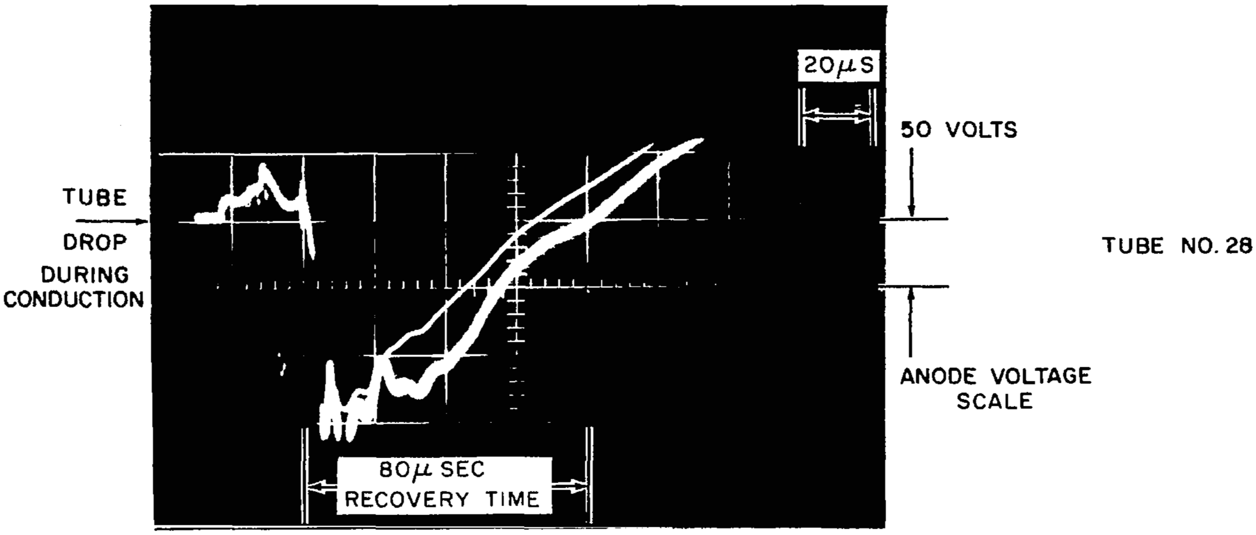

Figure 18 - Wave Shape for Recovery Time of 80 Microseconds

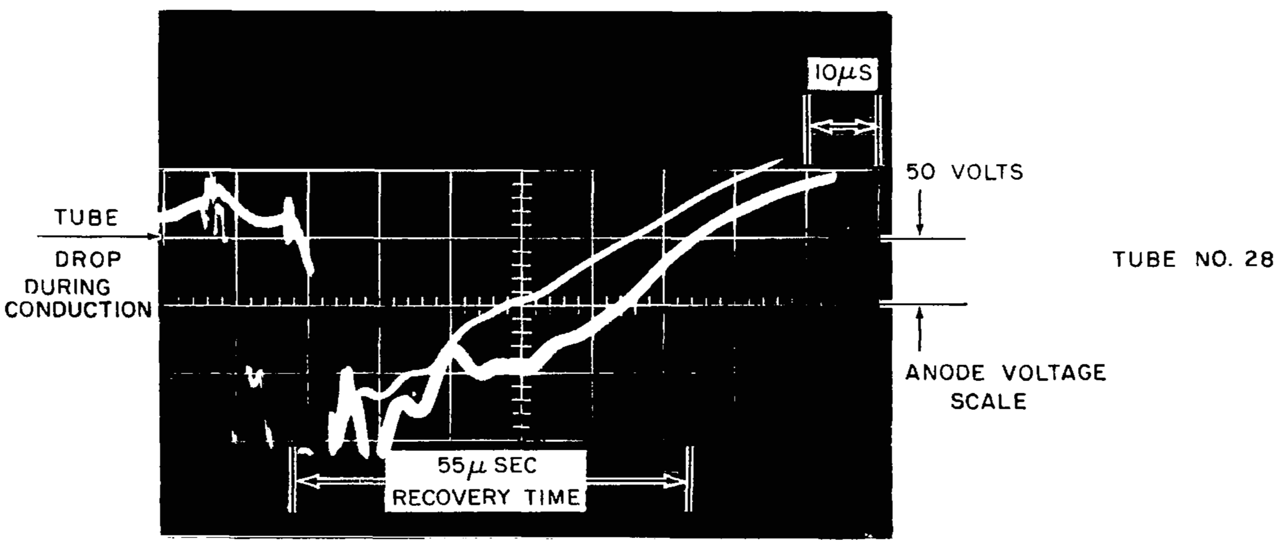

Figure 19 - Wave Shape for Recovery Time of 55 Microseconds

The first tubes to be paired for endurance testing were Nos. 28 and 30, and attempts at long-term operation revealed the need for resolution of conditions leading to breaker kick-outs or other tube instabilities. Operating conditions were varied with respect to recovery time, inverter input voltage, average current, and grid bias. A few hours of operation were obtained with recovery time set below 100 microseconds, but for the most part, recovery time was set at several hundred microseconds. This was done to increase circuit stability while certain problems in the trigger circuit were studied. Firing power in the trigger circuit was increased by changing the values of the trigger circuit capacitors C_3 and C_7, Figure 9, from 0.5 mfd to 1 mfd. A diode was also inserted between the trigger circuit and the grids of the cesium tubes to eliminate deionizing current from the grids at the start of each half cycle of anode current conduction. With these improvements, a run in excess of 50 hours without a kick-out or malfunction was realized with an allowed recovery time of several hundred microseconds. When the recovery time was gradually reduced to 100 microseconds, Tube No. 30 exhibited instability in the form of prefiring. This is a case of anode current commencing through the tube before the arrival of the trigger pulse at the grid, which causes the inverter to operate in an unbalanced manner and excessive current to flow through the tube that prefires. Attempts to eliminate prefiring with the tube running at objective ratings were unsuccessful. The prefiring did not occur at average currents below 10 amperes.

Rather than operate at a reduced current on endurance test, it was decided to remove No. 30 (at 193 hours) and hold it intact for future study. No. 31 would take its place.

When Nos. 28 and 31 were paired, No. 31 required a recovery time of about 150 microseconds unless the reservoir temperature was kept below 190°C. The allowable reservoir range was significantly increased when a 1-mfd capacitor was connected between the anode and cathode of No. 31. This had the effect of slowing down the rate of fall of inverse voltage after conduction from 600 volts per microsecond to 20 volts per microsecond. Endurance testing was therefore continued with this capacitor in place and with full objective test conditions, as cited below:

Anode Voltage	250 volts
Average Current	15 amperes
Repetition Rate.	200 pulses per second
Recovery Time.	100 microseconds

The next 2000 hours of endurance testing were generally uneventful except for the fact that No. 31 drew progressively more grid current. This was countered by increasing the bias supply voltage or by reducing the grid circuit resistance as the tube required. At 2024 hours, testing of No. 31 was discontinued due to the lack of proper grid control. Analysis revealed that the top cathode shield (iron) had eroded severely and that this material had been deposited rather loosely on the grid, hence creating the grid emission difficulty. A copy of the failure report that was issued for No. 31 is given in Appendix B.

At this juncture, No. 31 was replaced by No. 30 (which had previously been removed from test because of prefiring). The tube was started this time with the capacitor connected between the cathode and anode, and no prefiring was observed.

The original 3000-hour endurance test objective was completed with this pair of tubes still operating satisfactorily. However, since ultimately such tubes might be used in long-term space missions, the test was continued for the purpose of logging additional hours.

After an additional 100 hours of time, No. 28 failed (at 3112 hours total) for lack of cesium, and tests revealed that there were one or two small leaks at the bottom end of the envelope. The tube history indicated that there had been a leak problem on exhaust and that the tube had been repaired by painting with a silicone resin to patch the leak. Apparently this resin decomposed after 3000 hours at 300°C (in vacuum environment) allowing the original leak to open again. A copy of the report that was issued for No. 28 at the time of failure is given in Appendix C. The tube was not rebuilt because the leaks were not considered repairable.

No. 28 was replaced by No. 32, but at this point No. 30 started prefiring again at full load; thus full load testing was discontinued.

The final tabulation of tube operating hours in the inverter was as follows:

No. 28	3112
No. 30	1119
No. 31	2024
Total . . .	6255

DISCUSSION

As a result of endurance testing, three problems were discernible:

(1) flare-up

(2) prefiring

(3) erosion of cathod shield

All of the above results from an excessive demand for current density from portions of the cathode. This is a consequence of the constricted grid and/or cathode baffle design provided to achieve the short deionization time. Flare-up may be described as a transient, abnormal condition occasionally observed in the constricted-grid tubes and usually associated with excessive anode-cathode voltage drop. This condition was observed intermittently when:

(1) the tube was conducting high peak current with a low average current;

(2) a DC load was applied after a quiescent no-load period; or

(3) a substantial increase in DC loading was suddenly applied to the tube.

Flare-ups were temporary and appeared to last for only a few seconds. This time constant is considered to be that needed to bring about a new thermal equilibrium at the cathode. The condition of high tube drop was attended by an increase in the intensity of the glow visible through the bottom ceramic (hence, the designation "flare-up"). Simultaneously, a reduction in cathode heater current was also observed. This phenomenon was not present if the increase in DC loading through the tube was at a gradual rate, and it has never been observed in the steady state.

The cause of the condition was reasoned to be as follows. With six narrow slots at the grid and four slots in the shield atop the cathode, and with close spacing between the grid and shield, there exist four relatively independent paths between the cathode and anode in which plasma can exist. There is no way to ensure an equal distribution of emission from the full area of the cathode. Rather, the current may start through one channel and overload that channel before one or more additional channels ionize and share the load. The one-channel mode also concentrates emission from the cathode, causing it to experience hot spots.

The same phenomenon can occur in tubes that are not of constricted-grid design, but to a much smaller extent, since ion diffusion and communication from one channel to another is greater.

The cesium tube design has not been optimized with respect to this phenomenon. An improvement program would include:

(1) opening up the cathode region by:

(a) eliminating the slotted cathode shield,
(b) increasing the width of the slots in the shield

(2) substituting an indirectly heated cathode for the filament.

Performance relative to prefiring and erosion of the cathode shield should also be improved by the design changes recommended for reducing the flare-up condition.

In addition to the aforementioned observations, other tube characteristics that can be delineated as a result of testing will now be summarized.

All thyratrons tested appeared capable of operating at inverse ratings up to 300 volts.

The maximum overload current capability was not studied in depth since this type of testing tends to be destructive, and the tubes were limited in number. We have observed, however, an increase in average current from 15 to 25 amperes in special tests in the inverter when a tube loses grid control or fails to recover with no sign of distress in the tube. From this we would judge that the tube is capable of at least 100-percent overload for one second.

Anode delay time varies from a fraction of a microsecond to 25 microseconds. When fully loaded, the turn-on time is usually in the range of 10 to 25 microseconds.

All tubes of the design selected for endurance testing had recovery times of 100 microseconds or less. In the inverter, recovery times as low as 55 microseconds, could be achieved, but endurance testing was performed with the inverter circuit set to provide a recovery time of 80 to 100 microseconds.

Although some tubes were capable of operating in the inverter with a rate of fall of inverse voltage of 600 volts per microsecond, at least one, No. 31, required a reduction of this figure to 20 volts per microsecond. Tests on a larger sample of these devices would be required to establish a range of anode voltage rates suitable for reliable operation.

The rate of fall of anode current was not studied since all tubes were capable of operating in the inverter circuit without any restraining inductance. The rate of fall of current in the "wide open" inverter circuit was measured at 10 amperes per microsecond. Inductances to 400 microhenries were added a couple of times when a tube was performing poorly, but the reduced di/dt yielded no beneficial results.

With respect to commutation factor -- which can be defined as the product of (dv/dt) (di/dt) in volts and amperes per microsecond, respectively -- it was found that all cesium tubes of the "endurance test" design were capable of operating with a commutation factor of 200, whereas some tubes demonstrated a capability of 6,000.

Because of the limited number of tubes, and because of the problems already cited with respect to operating them at the objective level of 15 amperes, no attempt was made to study the tube at levels higher than 15 amperes average. With further design optimization, as has been suggested, it is felt that the life of the cesium tube at 15 amperes average can be substantially improved. Based upon the experience with three tubes, the average life of the design described herein is 2,000 hours. With no further design optimization it is felt that the cesium tube should demonstrate a substantially improved life at 10 amperes average. This estimate is based upon the following considerations:

(1) Anode delay time is shorter and steadier at 10 amperes average than at 15 amperes.

(2) The phenomenon of prefiring does not exist at average currents below 10 amperes.

Based on the data currently available, tentative ratings for the cesium thyratron are given in Appendix D.

Ultimately, power conditioning devices will require ratings of several hundred amperes, and much of the cesium-vapor technology developed at the 15-ampere level will also be applicable at these higher power levels. It is recommended that future high-powered cesium-vapor thyratrons embrace two features not in the present design:

(1) An indirectly heated cathode.

(2) One circular grid slot long enough or with sufficient area to carry the full tube current. This single slot design would permit the plasma to spread easily, and it would not be necessary to break down a new slot or channel when one became overloaded. Both flare-ups and cathode erosion would then be substantially reduced without sacrifice of short deionization time capability.

CONCLUSIONS

(1) The cesium thyratron design, represented by the four tubes (Nos. 28, 30, 31 and 32) built for the 3000-hour endurance test, has been proven to have a 100-microsecond recovery time in inverter operation.

(2) Three tubes were needed to accomplish the 3000-hour endurance testing. The average life per tube was 2000 hours, with a maximum observed life of 3142 hours.

(3) For the 15-ampere level, further design optimization is needed for a 10,000-hour life. Such optimization is needed in the cathode region of the tube.

(4) Without additional design optimization, the present cesium-vapor thyratron should have a much longer life if the average current loading is restricted to 10 amperes average.

(5) The design concepts which were demonstrated during this program may be applied to thyratrons of much higher current ratings.

(6) All cesium thyratrons demonstrated the ability to withstand a commutation factor of 200.

(7) Anode delay time tended to be long in these tightly constricted cesium thyratrons and was also a function of anode current.

(8) The cesium tube was subject to "flare-up" following a sudden increase in load current and, conversely, was stable if the average current was held at one value.

Appendix A

START-UP PROCEDURE FOR USE AT LOW TEMPERATURE

The following instructions were devised to avoid damage to cesium tubes when started from a cold state in the inverter. Some similar procedure should be used in other equipments also if external heaters and ovens are not adequate to raise the temperature of the tubes to 225°C.

START-UP OF CESIUM TUBES

Cesium tubes may be damaged if voltage is applied when the tubes are too cool and the vapor pressure is too low. In general, all parts of the cesium tube should be up to 225°C before regular operation is attempted.

Depending upon the particular set-up, it may be necessary to go through a specialized routine to prepare cesium tubes for operation. Such a routine follows:

1. Turn on anode heaters and tube filaments.

2. The reservoir heater should be adjusted so that the reservoir temperature will equilibrate at about 220°C.

3. Allow the tubes to heat until the coolest part of tubes has reached 150°C.

4. When item 3, above, has been satisfied, the tubes may be further heated by using anode current conduction, starting with low levels of current.

   (a) Set anode power supply to 125 volts DC.

   (b) Eliminate all commutating capacitance.

   (c) Set the loads to highest resistance.

   (d) Connect DC scopes or voltmeters between the anodes and cathodes.

   (e) Turn on the DC anode supply. If one or more tubes do not start, kick the tube into conduction by turning up the trigger supply. Tube drop should not exceed 22 volts at any time, and anode current should not be increased until the tube drop has fallen to 16 volts.

(f) The anode current is increased by 1 ampere when the tube drop is 16 volts or less to a maximum of 15 amperes average.

(g) Keep conditions on all the tubes parallel, and let the slowest tube determine the rate of progress.

(h) Using the above procedure, DC warmup may be considered complete when the coolest part of the tube has reached 225°C.

5. Readjust the ovens and heater voltages for inverter operation, and load the tube using 125 volts DC. Commutating capacitors should all be connected.

6. When 15 amperes average has been achieved with 125 volts, the DC supply may be changed to 250 volts.

7. The anode and grid wave shapes should be observed for any evidence of trouble. It may be necessary to operate the tubes for about two hours at less than final conditions before equilibrium of all characteristics is achieved.

8. Make final adjustments, and operate under the desired inverter conditions.

9. If a flare-up in the bottom end of the tube is observed during the above procedure, the loading of the tube should be temporarily cut back.

Appendix B

FAILURE REPORT
Tube No. 31

The design and construction of tube No. 31 was similar to that of No. 28, i.e., both tubes were "tight" in order to achieve the 100-microsecond recovery time. Both tubes contained copper grids 1/4 thick, with six parallel slots about 1/32-inch wide. The cathode was housed in a shield structure of steel whose top member was a disc 1/8-inch thick containing four parallel slots 1/16-inch wide. These four slots were parallel to and directly below the four innermost slots of the control grid. Spacings from grid-to-anode and from grid-to-cathode were less than 1/16 inch.

Operating conditions in the inverter were 250 volts input, 15 amperes average, and 30 amperes peak per tube, and approximately 100 microseconds recovery time.

No. 31 was started on life test with a relatively weak bias circuit, that is about 20 volts at the bias supply with a 500-ohm grid resistor. After a short time, it appeared that instability, as judged by the number of kickouts, was increasing, and that stability could be improved by increasing the bias supply voltage. Kickouts were caused by the inability of a tube to recover or to withstand forward voltage, simultaneously resulting in conduction through both inverter tubes, excessive average current, and opening of the breaker. After several such increases the grid circuit was stiffened by reducing the grid resistor from 500 to 100 ohms. Each time that it was necessary to strengthen the grid circuit, it was noticed (on the oscilloscope) that the voltage at the grid of the tube during the non-conducting half cycle was not equal to the bias supply voltage, but was only 5 to 10 volts negative with respect to the cathode. In other words, the grid seemed to be clamped to the cathode to a degree as the result of grid emission or a discharge from grid-to-cathode. To maintain proper recovery time, No. 31 needed a minimum negative grid voltage of about 10 volts. Each time the grid circuit was strengthened the circuit was made stronger than the clamping action within the tube, thus forcing the grid voltage to the required 10 or more volts negative.

As life progressed, we wondered whether the trend would be progressive to failure or if there would be an equilibrium level established whereby emission enhancing material depositing on the grid would be counterbalanced by removal of same material by ion bombardment or some other process.

The phenomena herein described is illustrated graphically by the curve in Figure 20, which depicts the required grid current as a function of life for proper operation of tube No. 31. The plotted current is approximate since it was computed by dividing the grid bias supply voltage by the grid resistor ohms. It is easily seen that no equilibrium was established. At 1500 hours it was necessary to increase available recovery time to 100 microseconds and at 1800 hours to 120 microseconds. At the very end, the grid appeared to be tightly clamped to the cathode, and there was even some intermittent evidence of a DC short between grid and cathode.

When the tube was opened, there was nothing of interest in the grid-anode region, but there were two significant developments in the grid-cathode region.

Severe erosion of the steel shield atop the cathode had occurred, as shown in Figure 21, and deposition of the eroded material had taken place on the grid surface, as shown in Figure 22. At one point, the slot width in the shield had increased from 1/16 inch to approximately 1/8 inch. The areas of greatest build-up of steel on the grid were directly over the most eroded parts of the steel shield.

The increase in grid emission or clamping action throughout life is easily explained by the build-up of steel at the grid. The steel is deposited like shingles and/or stalactites, and the thermal path back to the cool copper grid is poor.

The following are possible causes of the steel erosion:

(1) 15 amperes average may be beyond the inherent capability of the tube.

(2) Excessive ion bombardment as a result of high current density in the slot.

(3) Steel shield participating in the cathode emission process and supplying a significant share of the average current.

(4) Local overheating as a result of dissipation caused by emission from the grid.

(5) Inadequate trigger power.

While not considered a part of the major problem, it was also observed that some erosion of the tungsten filament had occurred. This was in keeping with a reduced filament current at the end of life.

Cures might include one or more of the following:

(1) Lower average current rating for the tube.

(2) Elimination of the top shield. The first tubes with long recovery times contained no top shield. The top shield was added for two reasons, as attempts were made to reduce recovery time to 100 microseconds.

   (a) Effective spacing between grid and cathode would be reduced.

   (b) Trigger ionization would be focused to the grid slots as a result of the line-up of slots in shield and grid.

   A tube has not been made with a tight grid and no cathode shield, and the exact effect on recovery time and/or triggering could not be assessed without its elimination.

(3) The top shield, if needed, could be fabricated from different material; for instance:

   (a) Copper which would run cooler and be less apt to act as a primary emitter.

   (b) Molybdenum or tungsten whose vapor pressure at a given temperature is orders of magnitude lower than that for steel.

(4) Increased trigger current or modification of the trigger circuit.

Tube No. 28, with 2300 hours, has not displayed the troubles associated with No. 31. It has also been operated with a slightly different grid circuit. Since DC bias has not been required for the 100 microsecond recovery time, the grid has been returned directly to cathode through a 500-ohm resistance.

The failure of No. 31 should in no way negate the endurance tests. It is a type of failure that may not occur in every tube under the same operating conditions and, to some extent, its occurrence may be dependent upon operating conditions. It would appear that a simple change of material for the top cathode shield would substantially reduce, or completely eliminate, this type of failure.

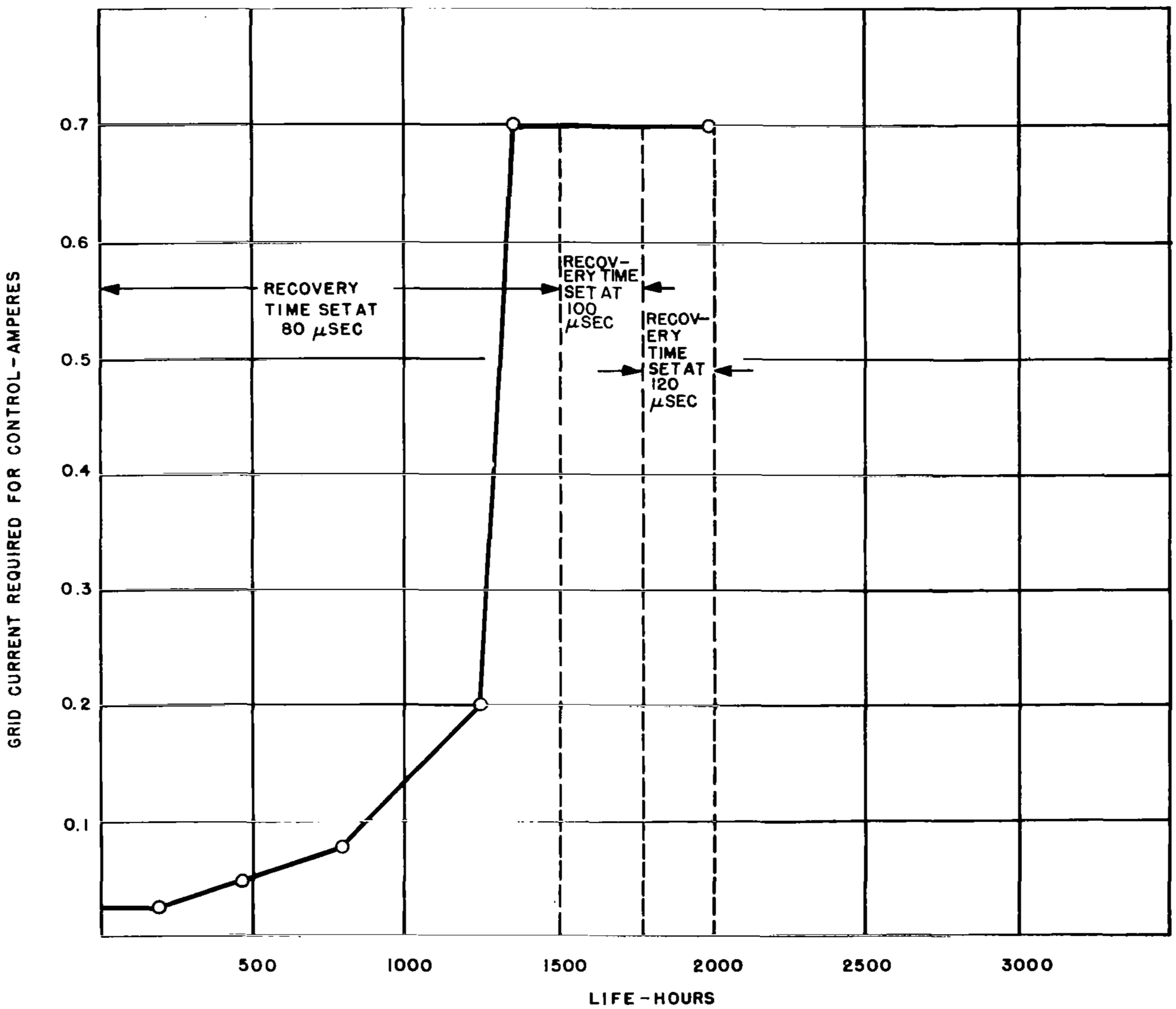

Figure 20 - Grid Current Required for Operation Versus Life
(Tube No. 31)

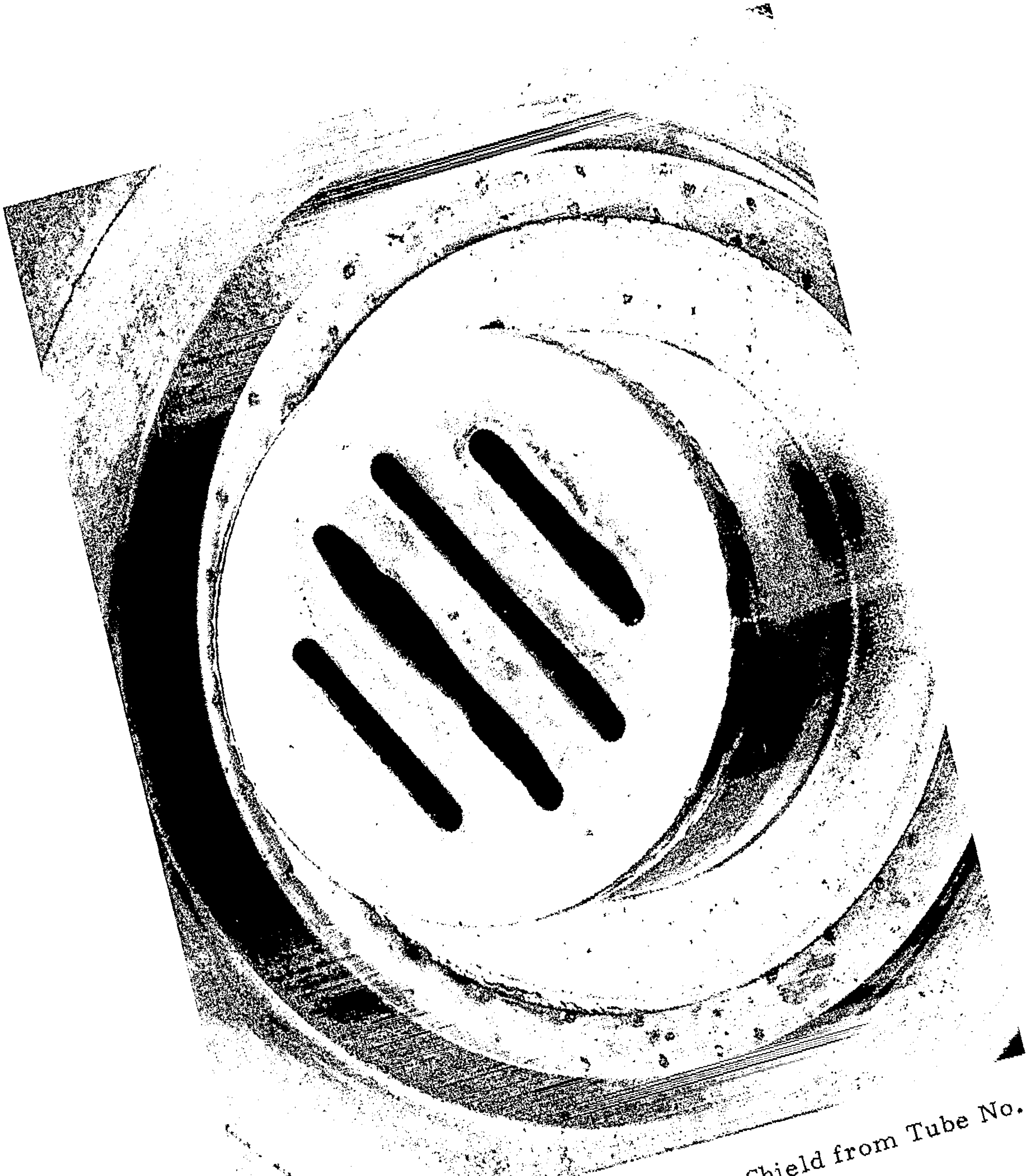

Figure 21 - Eroded Cathode Shield from Tube No. 31

Figure 22 - Contaminated Grid from Tube No. 31

Appendix C

ANALYSIS OF FAILURE OF TUBE NO. 28

This section of the report covers the operating history and analysis of the cause for malfunctioning of Tube No. 28 after 3112 hours of inverter service. No. 28 was the first tube in the development series to achieve the desired 100-microsecond deionization time.

Except for a few hundred hours at the start of testing, No. 28 was operated without a negative bias on the grid. This electrode was returned to the cathode through a resistor which was 500 ohms for part of the testing time and 100 ohms for the remainder. If not needed for recovery time, it is desirable to operate without grid bias. However, it frequently is necessary to use some bias to achieve adequate grid control. When operated in the zero bias mode described, No. 28 performed without incident for the entire 3100 hours.

At 3112 accumulated hours, however, the inverter stopped running, and in attempting to restart it, No. 28 was found to be acting abnormally. The tube would not conduct to the anode nor would the normal trigger pulse cause breakdown to the grid. It was believed that the tube was out of cesium either because of a leak or because of cleanup. Some conduction was observed by heating the tube some 50 degrees hotter than is usually required for conduction. This also pointed to cesium depletion.

The tube was removed from test and leak tested. One or two leaks were found near the cathode flange (Figure 23), although the exact locations were not pinpointed.

A review of the tube's history indicates that during construction there was a welding problem that required a number of attempts to make the joint between the grid and cathode subassemblies in the area indicated on the sketch. Finally, Nicoro brazing compound was also used to get a tight joint. However, at exhaust there was still some evidence of leaking at the bottom (cathode) end of the tube, and so this area of the tube was painted with a silicone resin compound that is often used as a vacuum sealer. A total of four coats was applied. It was concluded that the failure resulted from breakdown of the silicone seal due to gradual evaporation at high temperature for the extended period.

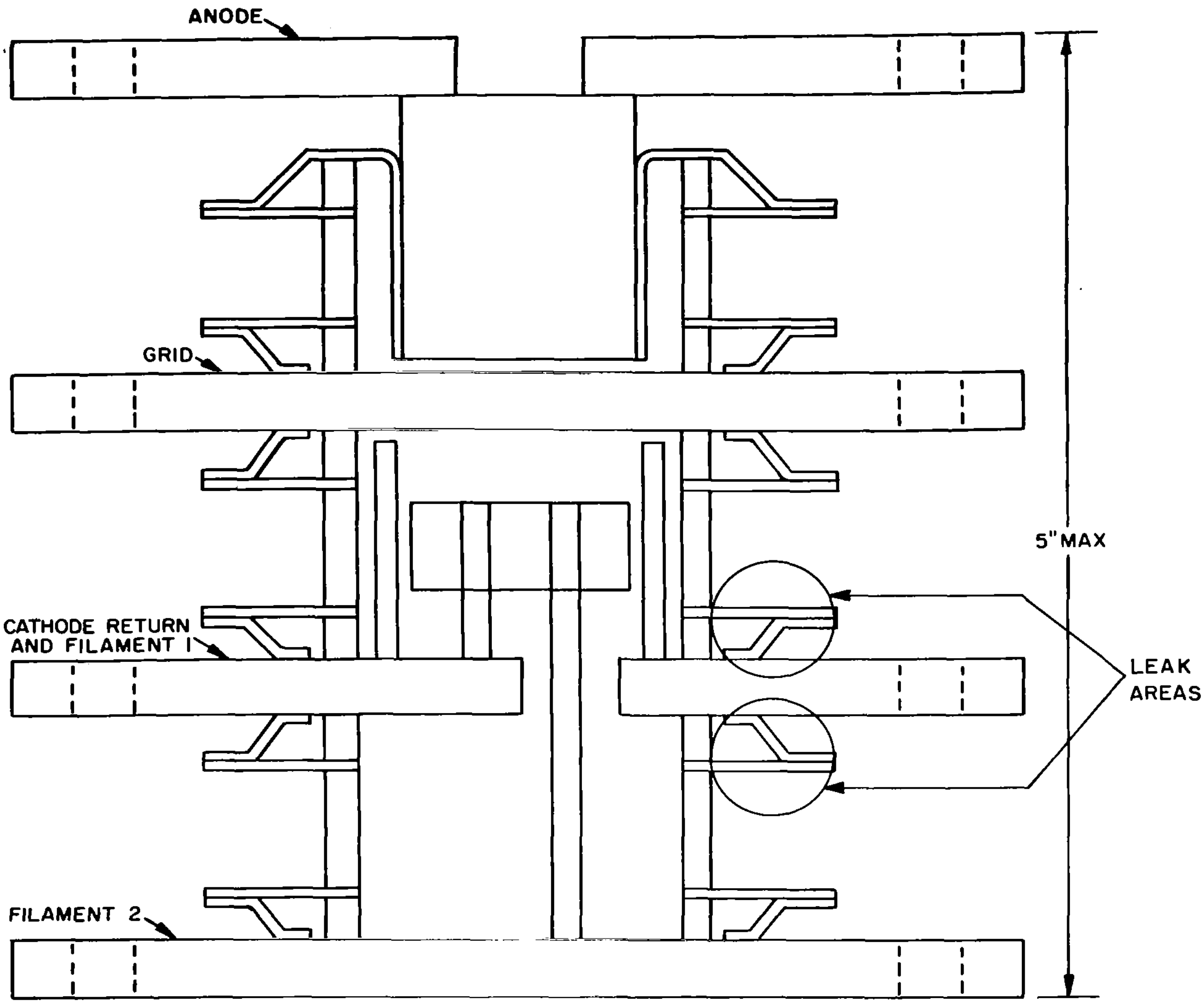

Figure 23 - Leak Areas on Tube No. 28

Appendix D

OBJECTIVE TECHNICAL INFORMATION FOR LOW-RECOVERY-TIME CESIUM THYRATRONS

The cesium thyratron is a tube for application where the environmental temperature is in the range of 200 to 300 degrees centigrade. While electrode and reservoir temperatures must be maintained by appropriate heat sinking, long life can be expected since its cathode is not subject to evaporation of emission enhancing materials. An outline view of the tube is shown in Figure 24.

GENERAL

Electrical

Cathode - Directly Heated

Filament Voltage	0.8	Volts AC or DC
Filament Current	60	Amperes
Deionization Time, Approximate	100	Microseconds
Ionization Time, Approximate	10	Microseconds
Anode Voltage Drop, Approximate	10	Volts

Grid Drive Requirements, Typical*

10 Microseconds Duration 250 volts x 50 amperes

Mechanical

Mounting Postion - Any

Net Weight, Approximate	5	Pounds

Overall Dimensions

Height, Maximum	6-7/8	Inches
Diameter, Maximum	4-1/32	Inches

Thermal

Type of Cooling - Conduction to Heat Sink**

Environment - Vacuum Maximum Pressure. .	10^{-4}	Torr

RATINGS, Absolute Values

	Typical	Maximum
Peak Anode Voltage (volts)		
Inverse	250	250
Forward	250	250
Cathode Current (amperes)		
Peak	30	50
Average	10	15
Negative Grid Voltage (volts)		
Before Conduction	50	50
Commutation Limits Δ		
dv/dt (volts per microsecond)	20	10
di/dt (amperes per microsecond)	10	10

The following boundary conditions prevail for temperature considerations:

1. Anode	250 C Minimum
	300 C Maximum
2. Grid	250 C Minimum
	300 C Maximum
3. Reservoir	200 C Minimum
	250 C Maximum

* Driver pulse measured at tube terminals with thyratron grid disconnected: Amplitude = 200 volts minimum, 300 volts maximum, above 0; Grid pulse duration = 10 microseconds minimum, measured at 70% of the peak amplitude; impedance of drive circuit = 5 ohms, maximum.

** Connections to heat sink may be made with 1/4" - 20 steel bolts and nuts. When making connections torque must not be transmitted through the tube body.

Δ The commutation period is the period in which the current is transferring from one tube to another. The di/dt is a measure of the rate of decay of anode current through the tube prior to cessation of current. The dv/dt is a measure of the rate of rise of inverse voltage at the anode after current cessation.

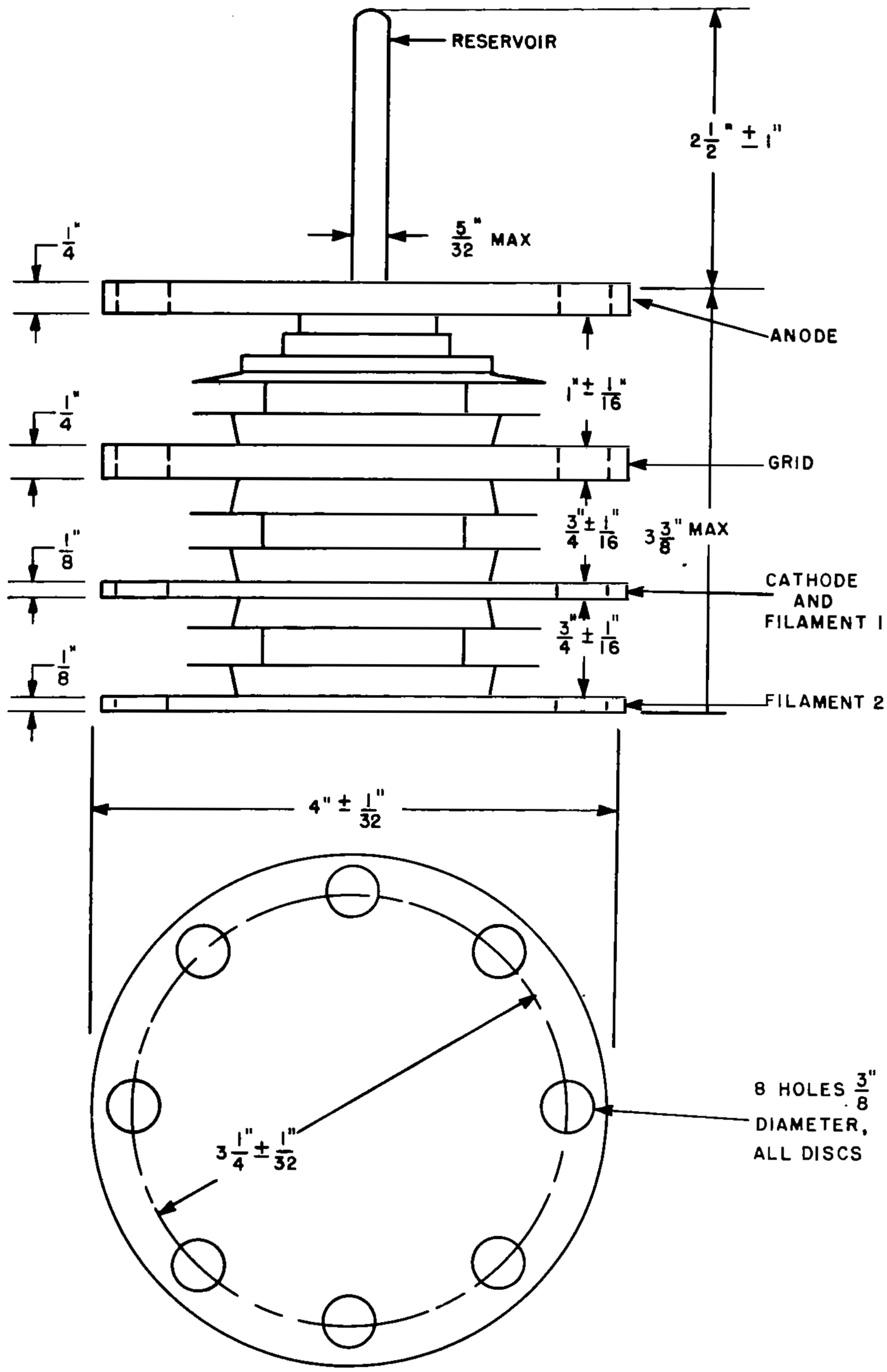

Figure 24 - Cesium Thyratron Outline

REFERENCES

1. Coolidge, Arthur W., Jr., Development of High-Temperature Vapor-Filled Thyratrons and Rectifiers, NASA Contractor Report, NASA CR-994, 1968.

2. Coolidge, Arthur W., Jr., Reduction of Recovery Time in High-Temperature Cesium Vapor Thyratrons, NASA Contractor Report, NASA CR-1417, 1969.